

FREE-FLYING MAGNETOMETER DATA SYSTEM ARCHITECTURE AND HARDWARE REALIZATION USING COMMERCIAL OFF THE SHELF (COTS) TECHNOLOGY

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Abstract

The Free-Flying Magnetometer (FFM) is an autonomous spin-stabilized "sensorcraft" developed at the Jet Propulsion Laboratory (JPL) for the Enstrophy sounding rocket mission. Four "hockey puck" (80 mm diameter, 38 mm height, 250 gram mass) FFMs, Figure 1, were successfully ejected from the payload of a sounding rocket launched from Poker Flats, Alaska on February 11, 1999. The FFMs measured the vector magnetic field at 4 points separate from the payload at relative distances up to 3 km, and telemetered their data, in bursts, to the ground. This first-of-its-kind mission acquiring in-situ multipoint magnetic-field measurements employing multiple free-flying instruments is enabling new science by measuring the fine-scale structure of the currents in the ionosphere involved in the production of aurora.

At the heart of the FFM is a sensitive 3-axis fluxgate magnetometer and an FPGA-based data subsystem that generates clocks and keeps time for tagging data, implements and maintains sensor interfaces, and generates control signals to manage power and data flow. The data subsystem sequencing is implemented with a master state machine that connects, through prioritized handshake interfaces, to state machines that control the system resources. This paper discusses the FFM data system architecture and design, integration issues related to power, noise, and timing, and its implementation using COTS technology.

Introduction

The Enstrophy mission was a collaborative project between the University of New Hampshire, Cornell University and JPL. The science goal of the

mission was the study of current filamentation phenomena in the Earth's northern auroral region through multipoint measurements of magnetic field. Any three direct, unambiguous measurements of the local magnetic field allow the local current density to be calculate ($J = \nabla \times B$). The mission technical objective was proof of concept of the JPL FFM design and demonstration of synchronized in-situ multipoint measurement of magnetic fields employing multiple free-flying sensorcraft.

Figure 1 is a photograph of a "Hockey puck" FFM. It is housed in a graphite composite shell with a patch antenna lid. The opening at 7-o'clock is the laser beacon. Sun sensors are located at 5-o'clock and 11-o'clock. The opening at 6-o'clock is a vent that allows out-gassing during launch. An opening for an IR photodiode that functions as an optical umbilical command link receiver, is at the

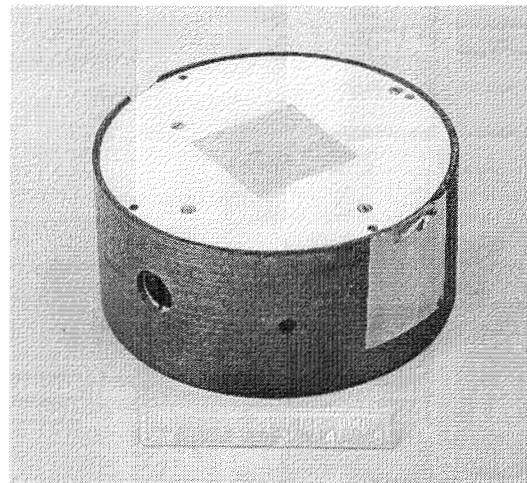


Figure 1. "Hockey puck" FFM that flew on Enstrophy mission. This photograph was taken after final vibration test. The metal foil tape covering the sun sensor at 5-o'clock was removed prior to flight

bottom center of the shell opposite the patch antenna. This opening is not visible in Figure 1. These FFM's contain a miniature 3-axis flux-gate magnetometer each having a measurement range of $\pm 60,000$ nT and a resolution of less than 2 nT. The FFM's were designed to be ejected from the payload spinning on their axis at around 11 Hz. The 3-axis flux-gate magnetometer sits in the center of the hockey puck. The x- and y-axis are in the spin plane while the z-axis is along the spin axis. The symmetrical, balanced hockey-puck form factor provides spin-stabilization during flight and facilitates a simple despin procedure for obtaining vector magnetic field from 3-axis data.

The FFM was designed and built using off-the-shelf commercial, industrial, and military grade surface-mount electronic components. Motivated by cost and schedule, this FFM design, targeted for a short sub-orbital flight, was kept simple, without fault tolerance or radiation requirements. The FFM flight experiment lasted for 15 minutes for the sub-orbital, 1071 km-altitude flight where three 5 minute data segments were acquired and transmitted in 26 second bursts to the 11-meter dish at Poker Flat. One of the primary technical challenges faced in developing the electronics for this FFM was minimizing electric and magnetic noise and its coupling to the sensitive integrated fluxgate magnetometer. Electronic components were screened for minimal magnetic signature.

Coupling was minimized through shielding, demagnetizing magnetic materials in packages and lead frames, minimizing the areas of current loops, and compensating offsets with properly positioned dc current loops.

The design, manufacturing, and test of the FFM units and discussion of instruments onboard the rocket which interfaced with the FFM's is reported in other publications [1].

FFM System Architecture

A block diagram displaying the FFM system architecture is shown in Figure 2. All control and data management functions are handled by the data subsystem. Commands to the FFM such as "Power On" are communicated through an infrared (IR) optical interface (Optical Umbilical). The data subsystem is implemented with a Xilinx XC4013E Field-Programmable Gate Array (FPGA). This SRAM-based gate array is configured on power-up via an AT17C256 serial EEPROM. The FPGA completes configuration initialization 270 ms after power-up, at which time its internal state machines are held in a reset state until the Power-On-Reset (POR) delay (1.4 sec) times out. This provides plenty of settling time for the voltage regulators supplying the analog electronics.

The data subsystem manages continuous data collection from four ADC channels and from

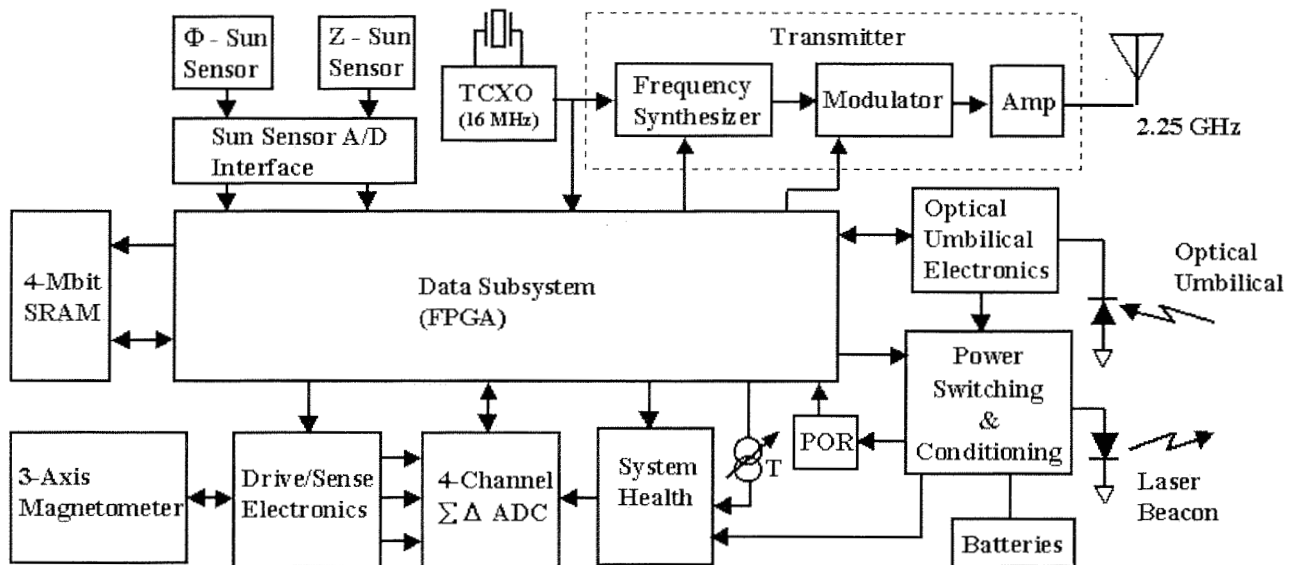


Figure 2. Block diagram of FFM system

two sun sensors. Three ADC channels are dedicated to magnetometer x-, y-, and z-axis analog outputs and the fourth channel to inputs multiplexed from eight sources: battery voltages and temperatures used for system health monitoring. Data frames, that are 128 bytes in size, are continuously built in SRAM. The whole 4 MB SRAM (Toshiba TC554161FTI) functions as a circular memory in which buffers of data frames are built. When the current buffer is filled (2547 frames, 292 seconds of data) the down-link process is started and a new buffer is created, so that no data is lost. The transmission process begins by powering the transmitter and initializing the frequency synthesizer so that it generates the desired carrier frequency. Each of the four FFMs transmit at a different frequency in the range of 2200 to 2300 MHz. The unmodulated carrier is transmitted for 15 sec to allow the ground receiver to lock up to the transmitter carrier, then 2000 zeros followed by the data are transmitted. The data in the filled buffer is transferred to the transmitter via a 32-bit First-In-First-Out (FIFO) memory. The data is clocked out of the FIFO at 100 kbps formatted to Non-Return-to-Zero (NRZ-M) and Viterbi encoded ($K=7, \frac{1}{2}$) and sent to the modulation input of the transmitter. After the 26-

second transmission, the transmitter is powered down to reduce noise coupling to the sensitive magnetometer and the SRAM buffer space is released so that it can be overwritten by new data.

IR Optical Umbilical Electronics

A functional schematic diagram of this IR link is illustrated in Figure 3. Four 9-bit serial pulse-width coded commands can be communicated between the sounding rocket payload and the stowed FFMs ("Power On", "Test", "Flight", and "Power Off"). The FFMs are turned-on by the "Power On" command and turned-off by the "Power Off" command or, when in Test mode, by an internally generated shutdown command. The "Test" and "Flight" commands place the FFM in a test mode or flight mode respectively. A direct high-speed path, which bypasses the encoder-decoder pair, is also provided for clock synchronization between the payload and four FFMs. A "Reset" pulse, originating from the payload GPS receiver, is issued after the FFMs are placed in flight mode. The Reset pulse initializes and synchronizes the clock and ADC onboard each of the four FFMs to the payload clock. The position of an FFM relative to the payload is

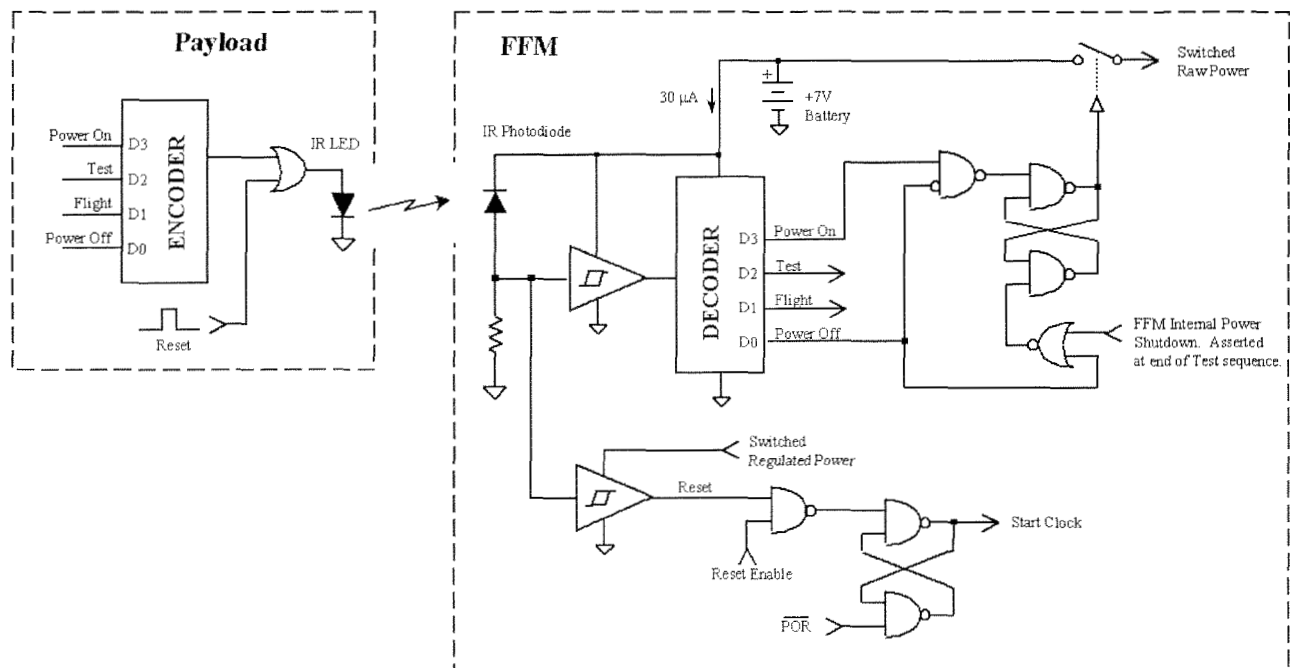


Figure 3. Functional schematic of optical umbilical used to send "Power On", "Test", "Flight", and "Power Off" commands and Reset pulse to FFM.

determined by the measured velocity of the FFM when ejected from the payload and by the time obtained from the FFM clock that is used to tag the data in the downlinked data.

The optical umbilical utilizes an infrared Light Emitting Diode (SHARP GL537) on the sounding rocket payload and a photodiode with built-in visible light cut-off filter (SHARP PD481) in the FFM. The photodiode signal is digitized using a low-power comparator (MAXIM MAX921) with threshold and hysteresis set to provide high noise immunity and correct functionality at moderate infrared background light levels. The pulse coded commands are generated and received using a low power CMOS encoder/decoder pair (Motorola MC145026 encoder/ MC145027 decoder). The IR optical command receiver electronics incorporating the photodiode, comparator and decoder were designed for minimum power consumption ($< 30\mu\text{A}$ from 7V battery). This extends the battery life to accommodate up to 60 days shelf life prior to launch.

Power Switching and Conditioning

The FFM power distribution scheme is illustrated in Figure 4. Seven high-capacity 3.5V Lithium Thionyl Chloride (Li/SOCl₂) batteries are utilized in the FFM: four batteries supply bipolar power for the analog sensor electronics and the digital power for the data subsystem, two power the transmitter and one powers the laser diode beacon. Voltage regulation is accomplished using low dropout linear regulator chips and power switching is performed with power MOSFETs having low R_{ds_on} (< 0.05 ohms). Switching regulators and high-side switches with on-chip charge-pump oscillators were avoided to prevent possible coupling with the sensitive magnetometer. All clocks required by the FFM electronics were derived from a single 16 MHz Temperature-Compensated Crystal Oscillator (TCXO). This prevents the possibility of frequency beatings between multiple clocks or induced harmonics and their coupling to the magnetometer synchronous-detector sense electronics. Multiple batteries were utilized to eliminate ground loops and support a single star system ground. A master dual power switch controlled by the IR command interface

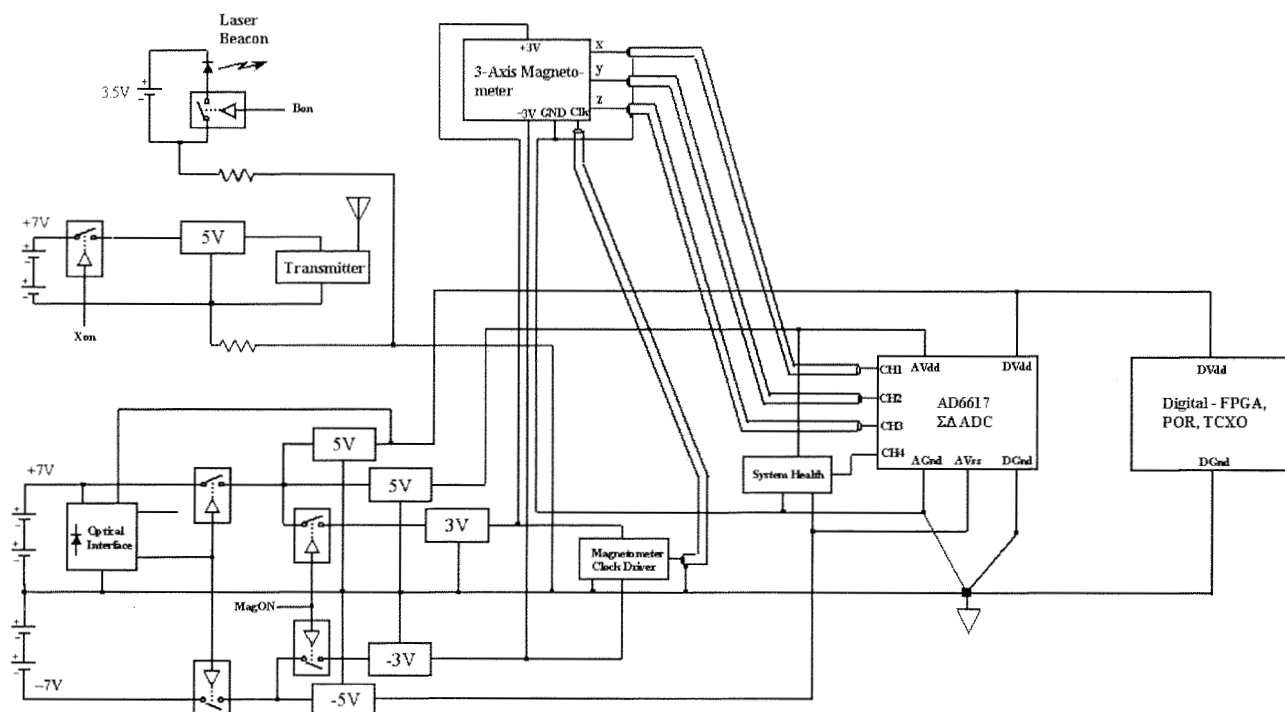


Figure 4. FFM power management and distribution.

supplies raw +7V and -7V power (4 batteries) to turn on the FFM. This power feeds five voltage regulators: +5V for digital electronics, +5V and -5V for analog electronics, and under switch control +3V and -3V for the magnetometer drive/sense electronics. Two dedicated batteries (+7V) under switch control are regulated to +5V for the S-band down-link transmitter. The final 3.5V battery, under switch control, supplies the laser beacon. Current-induced magnetic fields, seen by the magnetometer, were minimized through the minimization of current loop areas. This was accomplished by utilizing dedicated printed-wire board layers that overlay one another for power feeds and returns and by using twisted wire pairs for off-board connections.

Analog to Digital Converter

The Analog Devices AD7716 22-bit data acquisition chip handles all FFM analog-to-digital conversion needs. This device contains four 22-bit sigma delta A/D converter channels that synchronously sample their inputs. Three device pins are used to configure the device attributes through an on-chip control register. Completion of the POR delay, following the FFM "Power On" command, initiates the configuration programming of the ADC. The ADC channels are configured to sample at a rate of 279 conversions/sec, which sets the cutoff frequency at 73 Hz and the useable dynamic range to 108 dB or slightly more than 17 bits. The reset pulse transmitted over the IR command link is applied to the ADC reset pin to initiate synchronized conversion on the four ADC channels. Output data, formatted in twos complement coding, is accessed through a serial interface that is configured to operate in a slave controlled mode. ADC channels 1 - 3 are tied to the x-, y-, and z-axis magnetometer outputs and one out of every two data points are saved on these channels. Antialias low-pass filters having a 3 dB roll-off of $279/2/2 = 69.75$ Hz are utilized on these ADC channels.

System Health

ADC channel 4 is cyclically multiplexed to four temperature sensors, three battery voltages, and to the zero-signal baseline voltage of the temperature-sensor electronics. Temperatures are monitored at the magnetometer core, magnetometer drive/sense electronics board, ADC, and TCXO.

In addition, +7V and -7V FFM system batteries and +7V transmitter battery voltages are scaled to a magnitude of 2V and multiplexed into ADC channel 4. One out of every 32 data points is saved on this ADC channel. The ADC channel 4 input is attenuated by 23 dB to reduce cross-talk coupling to the other three channels. This is required because of the step changes that occur between the multiplexed system-health inputs, the ADC's -85dB channel-to-channel isolation, and the need to reduce crosstalk to the other three ADC channels to less than one LSB (38 μ V). Temperatures can be measured from -40°C to +50°C at a resolution of 0.0246°C/bit and battery voltage resolved to 2.95mV/bit.

Sun Sensors

The spin orientation of the FFM is obtained by two methods, one utilizing the laser beacon and the other utilizing the sun sensors. The laser beacon is used when in the dark. A fan-shaped laser beam emitted by a 670nm laser diode and aligned along the spin axis is detected by an array of sensitive large-area avalanche photodiode detectors on the side of the slowly rotating (~1Hz) rocket payload. The sun sensors are used at high altitudes while in the sun. The two sun sensors integrated in the FFM are mounted 180° apart looking radially outward. The sun sensors have a field of view of approximately 4° x 170° and generate a Gaussian-shaped voltage pulse when they sweep past the sun. Each sun sensor is connected to one input of an instrumentation amplifier which removes any common-mode signal between the two sensors. Voltage comparators are used to convert the positive and negative going pulses at the output of the instrumentation amplifier into positive logic pulses corresponding to each sun sensor. The sun sensors utilize the FFM clock, which is a 32-bit counter that is reset to zero when the "Reset" pulse is issued through the IR command link prior to deployment from the payload and is hence incremented every microsecond. The clock accuracy and drift is dictated by that of the TCXO. It is designed so that the drift between any two FFM clocks in a 20 minute period is less than 3ms. The value of the clock at the leading edge and trailing edge of the sun sensor pulse are averaged to obtain the time at the Gaussian peak. This time, reduced to 4 μ s resolution, is stored in the down-link data frame.

FFM Data Subsystem

A block diagram of the FPGA-based data subsystem is shown in Figure 5. The main controller is at the heart of the data subsystem. It executes the test or flight routines initiated by "Test" and "Flight" commands received from the IR command link. The main controller communicates with the ADC interface controller, sun sensor interface controller, SRAM, clock, and serial down-link FIFO. The main controller also performs power management functions and initialization of the transmitter. Data flow between the other controllers and the main controller are accomplished through 16-bit parallel interfaces under 2-wire handshake control. Fifteen interacting state machines were utilized to implement all data subsystem control functions. Data flow is accommodated using a 16-bit on-chip data bus.

The AD7716 interface controller configures the ADC after POR, controls the serial data transfers from the ADC, and passes data to the main controller through a 2-wire handshake interface.

Every second conversion on channels 1-3 are saved as measurements. 17-bit data is extracted from ADC channels 1-3 (x-, y-, z-axis magnetometer data), but passed to the main controller as 16-bit values (words). Thus 16 consecutive measurements of 3-axis data is stored in 51 words. The system-health data on channel 4 is extracted at 16-bit resolution from the ADC and passed to the main controller with a dedicated 2-wire handshake interface. Every 16th conversion on channel 4 is saved as a measurement.

The sun sensor interface controller responds to the leading- and trailing-edges of the digital pulses arriving from the sun sensor electronics. The time at the center of the pulse (peak of Gaussian) is passed to the main controller through separate 2-wire handshake interfaces for sun sensor 1 and sun sensor 2.

The serial down-link FIFO is operational when transmitting data. This 32-bit serial FIFO consist of two 16-bit shift registers that can be loaded by the main controller. Data is shifted out of

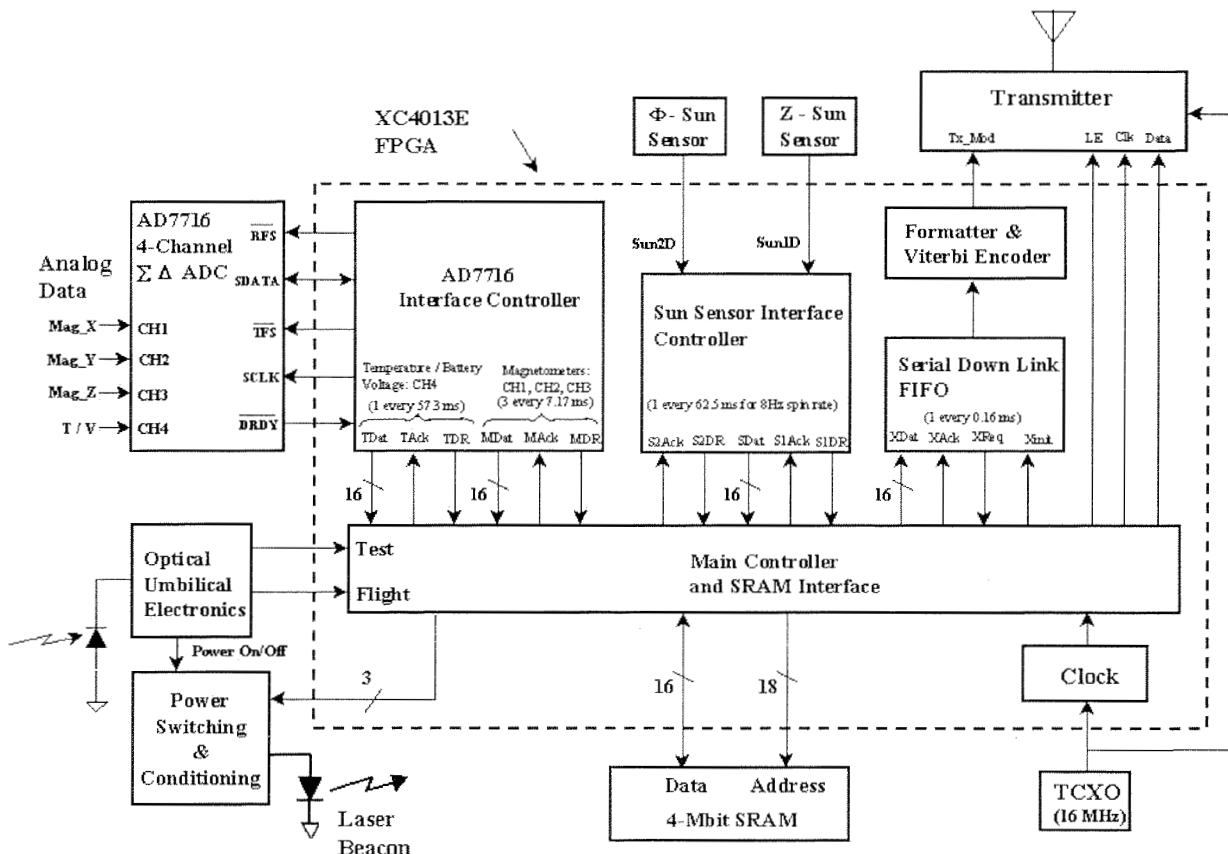


Figure 5. FFM data subsystem

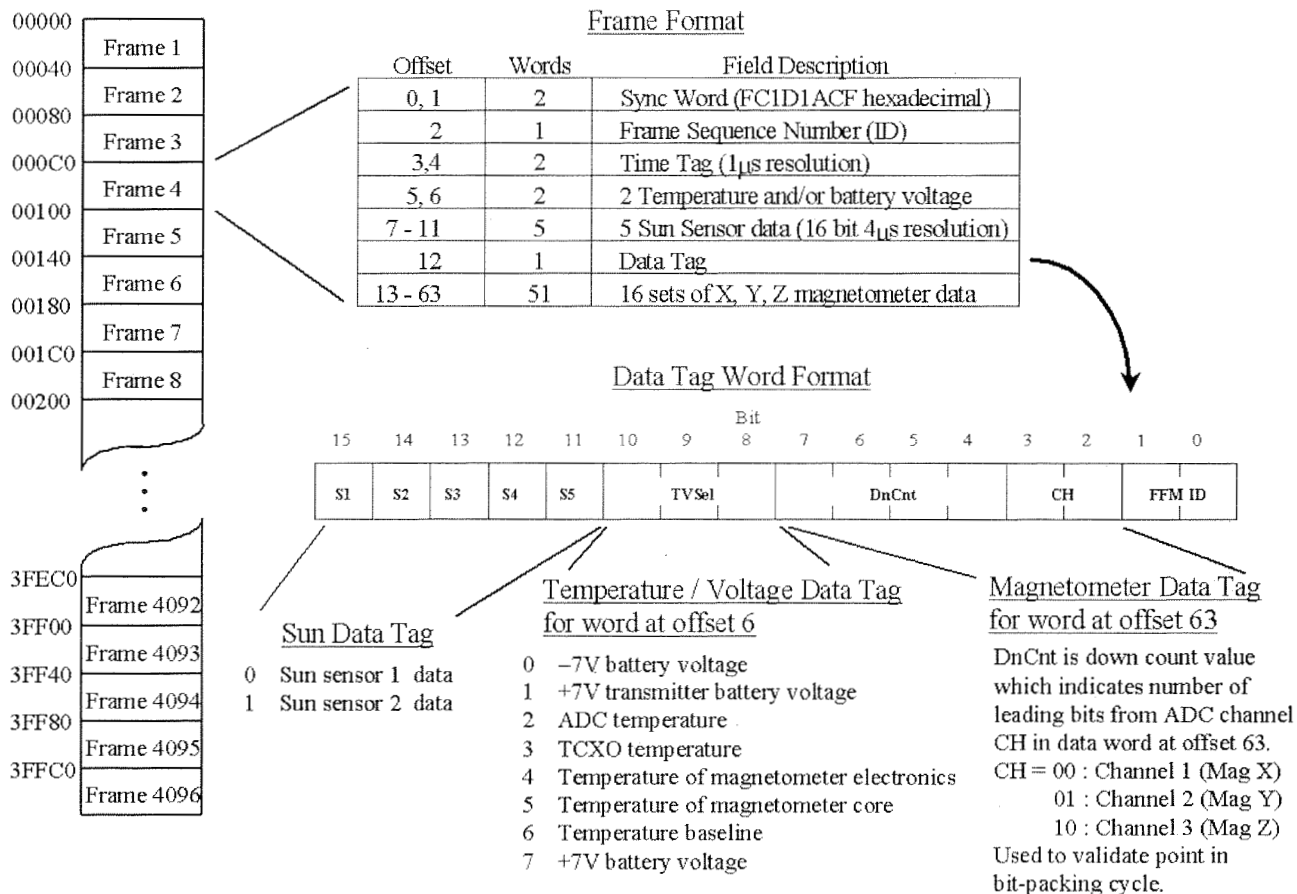


Figure 6. SRAM memory map and down-link frame format.

one while the other is loaded with new data. When the active 16-bit shift register empties, the other takes over and a data request is issued to refill the emptied register. Data is passed from the main controller to the FIFO under 2-wire handshake control.

The main controller writes the data to SRAM in down-link frame format. Figure 6 illustrates the frame format and SRAM memory map. Each data frame consists of 64 words (128 bytes). The first two words are a fixed sync pattern having a high autocorrelation. The sync bits occupy 3% of the frame and allow frame synchronization of the serial down-linked data. The next word is a frame identifier (ID). The frame ID is incremented for each new frame starting with one. The next two words is a frame time tag obtained from the FFM clock when the frame is first opened. The next two words hold two system health measurements. A 3-bit field in the data-tag word identifies which of the 8 system health measurements occupies these locations. Sun sensor data (4 μ s resolution) occupies the next 5 words.

These words are initially zeroed to indicate no data. Five words can accommodate a maximum spin rate of 21.8 Hz. Note that the upper 14 bits of each sun sensor reading are not explicitly stored, but can be reconstructed using the frame time tags in the previous, current, and next frame. A bit in the data tag word for each sun sensor word identifies the source: sun sensor 1 or sun sensor 2. The data tag word also has a 2-bit FFM ID and 6 bits that indicate the phasing in the cycle that packs 17-bit magnetometer data bits into 16-bit words.

A down-link buffer (2547 frames) occupies 62% of the SRAM address space. Each frame takes 0.1147 seconds to fill as determined by the saved magnetometer data rate (140 samples/sec). When the buffer fills, the down-link transmission process is initiated. This required 41 seconds (15 sec carrier only + 26 sec data). During this time, 357 frames are saved in the next buffer in SRAM. The magnetometer measurements in these frames will have a higher noise content due to coupling from the powered transmitter.

A state diagram that embodies the overall functionality of the FFM is shown in Figure 7. After initialization, following power on, the FFM waits for a "Flight" or "Test" command over the IR command link. During this time the transmitter is powered and broadcasting carrier. The "Power On" command is issued before launch. This allows the ground receiver to lock onto the carrier signifying successful turn-on. The "Test" command is issued nightly, prior to the launch date, to verify the health

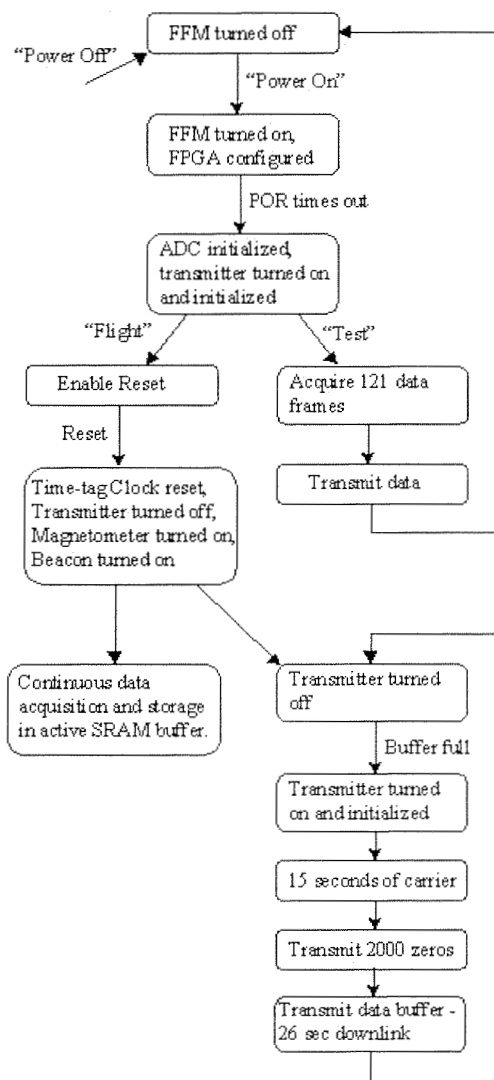


Figure 7. State diagram of overall FFM operation.

of the FFM and the state of the batteries. The drain on the batteries during the 20 second test is minimal. The batteries can easily support 30 days on the launch pad. Notice that the FFM automatically turns itself off after the test sequence

to conserve battery life. The "Power Off" command is also issued as a safeguard, because it unconditionally turns off the FFM from any state.

The rocket is launched with the FFMs in the powered on state. Then approximately 100 seconds into the flight (~300 km altitude), the "Flight" command followed by the "Reset" pulse are issued several times for redundancy. The FFMs are then deployed from the payload. The data system and transmitter are powered during the initial 100 seconds of flight to work-in the batteries [1].

Conclusion

The design, implementation using COTS components, and flight of "hockey Puck" FFMs, as part of the Enstrophy sounding rocket mission, was an overwhelming success.

Future FFM development will be directed at enhancing functionality and in further miniaturization. The technologies that will allow this include the use of monolithic magnetometers, Systems On a Chip (SOC) technology, and advanced packaging.

Acknowledgement

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References

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